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A LOCAL SEISMIC SURVEY AT CREIGHTON MINE

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M. Plouffe*

ABSTRACT

The Creighton Mine, Sudbury, was chosen as a test site to conduct a pilot survey using a portable seismograph recently acquired by CANMET. During the approximate two-month period, 208 seismic events were recorded. Of that number 183 were classified as blasts, and 22 were classified as mining induced seismic events, including a 3.6 m_N rockburst.

Waveform analysis was performed on these data. The results are in relatively good agreement with those from other Northern Ontario mines without any major discrepancies.

Key words: Mining Seismicity; Creighton Mine; Waveform analysis.

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UN LEVE SEISMIQUE A LA MINE CREIGHTON

M. Plouffe*

RESUME

A la suite de l'acquisition d'un séismographe portatif par CCTME, la mine Creighton fut choisie afin de conduire un levé pilote de la séismicité locale. Deux cent huit événements furent enregistrés durant une période de deux mois. De ce nombre, 183 résultèrent de l'enregistrement des explosions d'exploitation, et 22 furent classifiés comme événements induits reliés à l'activité minière, dont un coup de toit de magnitude 3.6 m_N.

Les résultats de l'analyse conduite sur les données recueillies permettent de conclure que les événements induits liés à l'activité minière se produisant à la mine Creighton se comparent raisonnablement bien avec d'autres enregistrés dans les mines du nord ontarien.

Mots-clés: Séismicité minière; Mine Creighton; Analyse des formes d'onde.

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INTRODUCTION

The monitoring and subsequent analysis of mining-induced seismic (MIS) activity in Northern Ontario became a mandate of CANMET (Canada Centre for Mineral and Energy Technology) in 1984 when the Canada/Ontario/Industry Rockburst Project was inaugurated (1). To implement these objectives, CANMET supports the operation of five regional seismographic stations and five macroseismic systems in Ontario mines that are experiencing rockbursts.

In order to carry out local seismic activity surveys in the epicentral distance range not covered by these two types of networks, CANMET acquired a state-of-the-art portable seismograph. Associated local surveys could contribute to aftershock surveys, coverage of the activity while the micro and/or macroseismic networks are not in operation, or to supplement these networks.

The Creighton Mine of Inco was chosen as a test site for this portable seismograph. This mine which is located on the southern rim of the Sudbury Basin in Ontario has, since 1984, been subjected to the largest mine-induced seismic (MIS) events ever recorded among the Sudbury mines and other mines in Northern Ontario.

During the pilot survey conducted in the fall of 1989, about 200 events were recorded. Of this total, 22 were classified as MIS events for which the largest was 3.6 m_N magnitude. This last event was the largest recorded in Northern Ontario during 1989.

It was the first time that analysis was performed by CANMET on data recorded at Creighton Mine. The results show that these data fit reasonably well with the analysis of data recorded in Northern Ontario mines.

SURVEY

A survey was conducted at Inco's Creighton Mine, located at Sudbury, between October 5 and December 13, 1989. A portable seismograph recorded

seismic events during this period, except for a 12 day interval between November 5 and November 17, when a power failure interrupted the readings.

During the summer of 1989, a previous attempt had been made to conduct a survey at Creighton Mine to monitor any seismic activity occurring during the annual shut-down. But due to power failures and hardware problems, it was unfortunately stopped before recording any mining-induced seismic events. However, a few blasts were recorded during this first survey.

These surveys were requested by both CANMET and Inco to test the feasibility of this new piece of equipment, the portable seismograph, and possibly to monitor any seismic activity located near Creighton Mine by the Sudbury Local Telemetered Network (SLTN) that was not detected by local microseismic networks.

INSTRUMENTATION

The equipment used for this survey was a PDAS-100 (acronym for Portable Data Acquisition System) which is a portable seismograph, made by Teledyne-Geotech.

During the survey, a full scale low-gain input of 2.0 volts was maintained, i.e., according to calibration the maximum peak particle velocity that could be recorded is around 250 mm/s. A trigger level was set up to have a lower threshold equivalent to 3.5% of the input ($\pm$70 mV). Therefore, all events generating a voltage higher than $\pm$70 mV should have triggered the seismograph. The triggered events are sampled at a rate of 1000 samples per second during a maximum window length of three seconds.

The sensor used consisted of a three-component surface accelerometer, a PA-20 (also made by Teledyne-Geotech). This sensor houses three orthogonal Geotech Model S-100 accelerometers. The piezoelectric devices have a frequency response ranging from 0.20 to 2000 Hz. However, for the needs of the present analysis only frequencies ranging from 1 to 400 Hz were utilized.

Also, the S-100 model has a full-scale output of ±2.0 times the gravitational acceleration (g).

LOCATION

The seismograph was deployed on the surface within the boundary of the Creighton mine property. One move was necessitated late in the survey.

The first location (Figure 1) was on an outcrop along the road between Shaft No. 9 and Shaft No. 11. The second location was on an outcrop near Shaft No. 5 hoist room, an the move was made on November 30, 1989.

At these locations the portable seismograph was about 2 km above the main foci of the recorded seismic activity.

EVENTS RECORDED

Two hundred and eight events were recorded by the PDAS-100 during the survey (Table 1a). After verification with the mine operator, 170 of these were also recorded by the Electrolab MP-250 microseismic networks installed at Creighton Mine. Only 38 events were not recorded by the local microseismic arrays.

After a comparison of the waveforms of the unrecorded events with the ones recorded and classified by the mine operator, 33 unrecorded events (Table 1b) were classified as probable blasts, and 2 as probable MIS events, one of which was reported to the mine operator (Table 3).

Three events did not fit conventional wave patterns. Table 2 lists the date and time when these events occurred, and Figure 2 shows the waveforms as recorded by the PDAS-100 on the accelerometer system sensor (z-component). No explanation can be given for these 3 events, but a strong impulsive onset and a short duration or coda is a common feature.

With regard to the 170 remaining recorded events, the majority were blasts (Table 1c). The percentage of blasts over the total number of recorded

events (84%) is similar to the previous percentage estimated (88%) for the Sudbury Basin (2). This could imply that, for the period of recording the recorded local seismic activity was similar in pattern to the regional activity recorded by SLTN, or alternatively, that the ratio of microseismic MIS events/blasts may be equivalent to the regional ratio for Creighton Mine.

Although the purpose of the survey was not specifically to report blasts, Figure 3 shows some types of blasts recorded by the PDAS-100 during the survey. On the basis of the mine operators classification, it was easy to differentiate the waveforms generated by slash, VRM (for vertical retreat mining), and crown blasts. These distinctive signatures are introduced by the shooting pattern and the delay parameters (3).

A total of 20 events recorded by the PDAS-100 were classified as mining-induced seismic events (Table 1c). Of this total, accurate locations could not be determined for 8 events - locations are usually derived using the MP-250 networks. The main reasons for the uncertain epicenters are that they occurred outside the arrays and so the networks gave a poor location for them, or they did not trigger the number of sensors necessary to activate the MP-250 software. Depth below surface ranged from 1 to 2 km.

Of the remaining 14 MIS events, 6 were also recorded by the Sudbury Local Telemetered Network. However, for one event, only 1 station recorded it. The remaining 5 were also recorded by the Eastern Canada Telemetered Network (ECTN) and so an m_N magnitude was assigned to them.

The magnitude range of these events was between 1.7 to 3.6 m_N (Table 3). Fortunately, the PDAS-100 was in operation on October 30, 1989, at 15:53 EST, and recorded a mining-induced seismic event of 3.6 m_N magnitude. This event is the largest recorded in the Sudbury Basin during 1989, and the largest that occurred at Creighton Mine since October 27, 1987, when a 3.7 m_N MIS event occurred there.

DATA ANALYSIS

The digitized signals of the selected events were analyzed first to determine travel path parameters such as peak particle acceleration and velocity, seismic energy, and P- and S-wave arrivals. Then an analysis of the seismic source parameters using the Brune model (4,5) was carried out in the frequency domain.

For unlocated events, the time difference between S- and P-wave arrivals was compared with one of the located events to increase the number of events studied. Table 4 lists the hypocentral distances of the located events against their S- P-time differences. Figure 4 shows the relationship between them assuming a uniform velocity:

Distance = 7.61 * time difference + 129 in metres. Eq 1

Hypocentral distances ranged from 980 to 2275 m.

In Table 4 and the following, an asterisk (*) after the date for one event shows that this event was not located by the MP-250 networks. The parametric values for these events are shown on selected figures but are not used to determine any empirical relationship.

A. PEAK PARTICLE ACCELERATION

The vector sum peak particle accelerations (PPA) measured during the survey range from about 140 mm/s^2 (around 1% of the gravitational acceleration, g) to 1440 mm/s^2 (15% g) for the 3.6 m_N event (Table 5).

For 11 events, the maximum peak particle acceleration is found in the P-wave (Table 6). This result apparently contradicts conventional earthquake seismicity theory in that the peak particle acceleration in the P-wave should be about three fifths that of the acceleration recorded in the S-wave.

B. PEAK PARTICLE VELOCITY

The vector sum peak particle velocities (PPV) measured are ranging between 0.09 to 5.23 mm/s (Table 5). These values are consistent with the trend given by Hedley (6), who defined, for the Ontario mines, the peak

particle velocity, distance and magnitude empirical relationship as:

$$\log(Rv) = 0.63\ M - 1.33 \qquad \text{Eq 2}$$

where, M = earthquake magnitude

R = hypocentral distance in m, and

v = peak particle velocity in m/s.

using the same empirical format as Spottiswoode (7), and Gibbon (8), who derived theirs for the South African gold mines. Figure 5 shows that the surface data from Creighton mine follow the same trend, but are much below the trend defined by Spottiswoode (7), and also below the underground data.

Hedley also defined this relationship in an equivalent format used for blasting:

$$v = 4000 \left(\frac{R}{10^{M/3}}\right)^{-1.6} \qquad \text{Eq 3}$$

The attenuation factor of -1.6 is calculated using data recorded on ground surface from Rio Algom's Quirke II Mine at Elliot Lake, and underground data from Creighton Mine. But, Hedley suggests that using only surface data would have accentuated this attenuation factor as the signal has to pass through considerably fractured zones surrounding the mining zones.

An attenuation coefficient of -2.8 (Figure 6) can be found using only the surface data from Creighton Mine, emphasizing his hypothesis. The scaled distance on Figure 6 is the ratio of R, the distance, over $10^{M/3}$. According to surface data only, Hedley's relationship would be:

$$v = 5000000 \left(\frac{R}{10^{M/3}}\right)^{-2.8} \qquad \text{Eq 4}$$

Taking both underground and surface data tends to decrease that attenuation factor, and the -1.6 factor calculated by Hedley could be used to define the peak particle velocity, distance, and magnitude relationship for the Creighton Mine. Only the constant factor would have to be modified so that Hedley's equation fits both data sets.

C. SEISMIC ENERGY

Cook (9) defined the energy radiated from a seismic source in an elastic medium as:

$$Es = 4 \pi R^2 \rho(\alpha \int^{Tp} Vp^2 \, dt + \beta \int^{Ts} Vs^2 \, dt) \quad (5)$$

where, ρ = density

α or β = compressional or shear wave velocity

R = hypocentral distance

Vp or Vs = ground velocity of P- or S-wave, and

Tp or Ts = duration of the seismic waves in P or S phases.

The total seismic energies listed in Table 5 are the sum of each axis as these axes were orthogonally deployed.

These seismic energy values have the same trend as that defined by Hedley (10), although they tend to fall below the line (Figure 7). This could indicate a larger deviation from a linearly elastic behaviour than the one observed by Hedley at Quirke II and Falconbridge's Strathcona, Sudbury, mines.

Figure 8 shows seismic energy of the P-wave which varies between 10 to 30% of the total seismic energy contour lines with an average value for all MIS events of about 22% in agreement with the observations by Hedley (10). Again, under these circumstances, the energy found in the P-wave cannot be ignored. These results may contradict the results of both Cook (9) and Spottiswoode and McGarr (11), who observed in mine tremors in South Africa that about 10% of the seismic energy can be found in the P-wave.

ATTENUATION

The following seismic source parameters are usually determined through spectral analysis, but these spectra should be properly corrected for the attenuation caused by the heterogeneities of the rock as the seismic waveforms are attenuated while propagating through the ground. The attenuation rate is

conventionally expressed by an average quality factor, Q.

The quality factor, Q, was determined using the technique of Tsujiura (12), whose straightforward method consists of taking the natural logarithm of the ratio of two spectral amplitudes at frequencies greater than the corner frequency thus:

$$\ln(f_2/f_1) = \pi(f_2-f_1)\ t^* \qquad \text{Eq 6}$$

is used to compute t^* which is the attenuation operator. This attenuation operator is equal to the total travel time of the wave divided by a mean Q (13,14). The spectra are thus corrected by multiplying each value by the exponential term $\exp(\pi\ f\ t^*)$ at each frequency f.

The average factor, Q, found for the shear wave for Creighton Mine is 60. This may reflect the high attenuation that could be found in a highly fractured region surrounding the mine, as the sensor is deployed above the mine.

SEISMIC SOURCE PARAMETERS

Seismic source parameters are based on the shear waves only. A fixed 0.5 second window was used to bound the shear waves and minimize contribution from crustal reverberations. A test was made using a one-second window instead. Generally, in the second case, a lower seismic moment and a larger corner frequency were found for the events.

A correction was tried on the shear wave spectra using a t^* of about 0.010, but as the correction factor was flattening the spectral density curve and even increasing the spectra values for high frequencies, it became very difficult to peg the corner frequencies, so no attenuation correction was applied in the present study for corner frequency calculations. This tendency could be explained by the fact that a Q value of 60 represents an average value and a much lower value should have been applied.

To obtain a final result for each event, plateau values for each axis

were combined as vector sums (15), and corner frequencies were averaged (16). On the basis of these plateau and corner frequency values, seismic moment, source radius, stress drop, and average slippage are calculated.

The following equations are derived from Brune's model (4,5), and are a convenient formulation for estimating mining-induced seismic source parameters. The equations to calculate the seismic moment (Mo), the source radius (Ro), the stress drop ($\Delta\sigma$), and the average slippage (ψa) are:

$$Mo = \frac{4\pi\ c^3\ \rho\ R\ \Omega o}{F\infty} \qquad \text{Eq 7}$$

$$\Sigma o = \frac{2.34\ \beta}{2\ \pi\ fo} \qquad \text{Eq 8}$$

$$\Delta\sigma = \frac{7\ Mo}{16\ Ro^3} \qquad \text{Eq 9}$$

$$\psi a = \frac{16\ \Delta\sigma\ Ro}{7\ \pi\ G} \qquad \text{Eq 10}$$

where, c = α or β the compressional, or shear wave velocity, respectively

ρ = density (2700 kg/m^3)

G = shear modulus = $\rho\ \beta^2$

R = hypocentral distance

Ωo = low frequency spectral density level

$F\infty$ = average radiation pattern factor (0.57)

fo = corner frequency

A. SEISMIC MOMENT

The seismic moment is a convenient measure of the size of any seismic events. It is related to fault dimensions and slippage along that fault. The concept of seismic moment is restricted to fault-slip events.

Seismic moment is usually compared to magnitude. Hasegawa (17) determined an empirical relationship between seismic moment and magnitude for earthquakes in the Canadian Shield:

$$\log Mo = 0.94\ m_N + 1.32\ (GN\text{-}m) \qquad \text{Eq 11}$$

Semadeni (16) and Hedley (10) present evidence to show that this

relationship is also valid for mining-induced seismic events in Northern Ontario. Figure 9 shows that the 1989 Creighton events also follow the same log-linear trend.

B. SCALING RELATIONSHIPS

Equations 8, 9 and 10 show that seismic source parameters are related to corner frequency and seismic moment (4) (when implying a circular fault model). These relationships associated with seismic moment are important when comparing small events with larger ones when no magnitude can be attributed to some events.

A constant stress drop pattern has been found for some earthquakes and mine tremors, although several recent studies are finding variable stress drops (13). This implies that corner frequency decreases as seismic moment increases, as shown by Figure 10. Straight lines are contours of constant stress drop. The majority of the data falls within a constant stress drop interval from 1 to 10 MPa.

For small events only, the trend is not consistent with the constant stress drop pattern (this pattern is also observed by Hedley (10)). Between 60 and 100 Hz, the corner frequencies are somewhat independent of the seismic moment. A broadening range of data is required to confirm this trend.

The other source parameters vary noticeably. The source radii vary between 15 to 130 m, while the average slippages range from 0.3 to 28 mm.

Regardless of whether this stress drop is constant or not, other empirical moment-related relationships can be found. The ground motion parameters $R\underline{v}$ and $\rho R\underline{a}$ depend on seismic moment. The peak velocity parameter ($R\underline{v}$) should scale according to $Mo^{1/3}$ (18), and the peak acceleration parameter ($\rho R\underline{a}$) should be independent of seismic moment.

Figures 11 and 12 show that these two relationships are applicable to the Creighton 1989 data. The peak acceleration parameters (Figure 11), despite scatter, appear independent of seismic moment, and the peak velocity

parameters (Figure 12) seem to fit well with the seismic moment to the one third power as indicated by the straight line on the graph.

THE OCTOBER 30, 1989, EVENT

Special attention must be paid to the October 30, 1989, 3.6 m_N event, mainly because it was the first time that an event of magnitude above 3.0 m_N was ever recorded so close to its location, and that a full study was performed on it. Prior to that survey, large MIS events were recorded by SLTN and the Canadian National Seismograph Network, but only by one-component sensors and from a distance of many kilometers.

The previous tables listed parmetric values as determined by data analysis. These data analyses were performed on the waveforms shown in Figures 13 to 15, and show data recorded: in acceleration mode, after integration, in velocity, and displacement modes, respectively. Note the conspicuous wave arrivals, especially the S-wave arrival on the y-axis on all Figures.

FOCAL MECHANISM

The focal mechanism solutions of the large MIS events that occurred at the mines around the Sudbury Basin show a tendency of thrust-fault-slip on intermediate-dipping planes (19). However, the focal solutions of these events are poorly defined due to a lack of well-distributed data over the focal sphere, especially in the southern quadrant.

The evidence of non-double-couple due to volume closure, components for any MIS events from Sudbury mines must await a detailed instrumental coverage of the epicentral region and an adequate knowledge of near-source crustal structure so that a reliable Green function can be determined. Since the non-double-couple component generally contributes a minor percentage (a few tens of percent) of the total radiated energy (most of the energy from the fault-

slip), a very careful moment tensor inversion is required to detect the non-double-couple component (13).

The October 27, 1987, MIS event of 3.7 m_N gives a moderately 'well-defined' mechanism solution of all the ones studied since 1984. A focal mechanism analysis was carried out for the October 30, 1989 event, but because of a lack of data no solution was found. Figure 16 shows the data distribution for the 3.6 m_N MIS event with the 1987 event solution superimposed on it. This 1987 solution seems an appropriate preliminary solution for the 1989 event.

As reference, the October 1987 event has the following focal plane parameters: strike 163.0°, dip of 55.6°, and rake of 77.8°.

FUTURE INVESTIGATIONS

These preliminary results introduced some interesting features of mining-induced tremors that should be addressed in subsequent studies.

Studies on the incident waves should provide more information on the source itself. Similarly, with the peak particle accelerations and/or velocities that are observed in the P-waves, are they the results of source mechanisms or propagation path, or both? The high percentage of seismic energy found in the P-wave compare to earthquake seismology theories that should also be investigated which should shed more light on subtle differences between mining-induced tremors and natural earthquakes.

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Table 1 - Classification of events recorded by the PDAS-100

Table 1a - Classification of events

Events recorded by MP-250	170	82%
Events not recorded by MP-250	38	18%
Total	208	

Table 1b - Classification of unrecorded events

Blasts	33	87%
MIS event	2	5%
Unknowns	3	8%
Total	38	

Table 1c - Classification of recorded events

Blasts	150	88%
MIS events	20	12%
Total	170	

Table 2 - List of the unknown events, 1989

October	16	289	03:56 EDT
December	05	339	10:01 EST
December	11	345	21:36 EST

Table 3 - List of the MIS events

Date 1989		Julian Date	Local Time	Location	Magnitude
October	21	294	06:19	No location	
"	23	296	01:23	"	1 station
"	25	298	13:40	"	
"	28	301	01:02	"	
"	28	301	07:58	Location given	1.7 m_N
"	30	303	15:53	" "	3.6 m_N
"	30	303	15.57	" "	
"	30	303	15:59	" "	
"	30	303	17:05	" "	
"	30	303	21:18	" "	
"	31	304	15:03	No location	
November	03	307	18:07	Not recorded	
"	05	309	05:24	Location given	
"	19	323	05:54	" "	
"	19	323	05:54	" "	2.7 m_N
"	19	323	05:59	" "	2.4 m_N
"	25	329	19:35	Reported only	
"	28	332	15:41	Location given	
"	29	333	12:42	" "	
"	30	334	07:43	" "	
December	08	342	21:10	No location	
"	12	346	23:26	Location given	2.6 m_N

Table 4 - List of hypocentral distances and S-P time diffences

Date 1989		Local Time	Distance (m)	Time Diff. (m sec)
October	21*	06:19	1515	0.19
"	23*	01:23	1705	0.21
"	25*	13:40	1270	0.15
"	28*	01:02	1605	0.19
"	28	07:58	2080	0.25
"	30	15:53	2090	0.26
"	30	15:57	1965	0.23
"	30	15:59	2115	0.26
"	30	17:05	2120	0.26
"	30	21:18	2060	0.25
"	31*	15:03	1615	0.19
November	03*	18:07	980	0.11
"	05	05:24	1550	0.19
"	19	05:54	2140	0.27
"	19	05:54	2130	0.28
"	19	05:59	2125	0.26
"	25*	19:35	990	0.11
"	28	15:41	2275	0.28
"	29	12:42	2125	0.25
"	30	07:43	1555	0.20
December	08*	21:10	1775	0.22
"	12	23:26	1810	0.21

* Unlocated events.

Table 5 - List of seismic parameters

Date 1989		Local Time	Seismic Energy (kJ)	PPA (mm/s^2)	PPV (mm/s)
October	21*	06:19	210	190	0.19
"	23*	01:23	210	220	0.18
"	25*	13:40	1770	330	0.63
"	28*	01:02	370	250	0.19
"	28	07:58	10040	650	1.00
"	30	15:53	600740	1440	5.23
"	30	15:57	720	250	0.25
"	30	15:59	1090	270	0.22
"	30	17:05	4130	320	0.44
"	30	21:18	2650	270	0.37
"	31*	15:03	280	310	0.21
November	03*	18:07	1620	390	0.68
"	05	05:24	220	300	0.24
"	19	05:54	14720	330	0.59
"	19	05:54	31060	380	0.79
"	19	05:59	6750	300	0.37
"	25*	19:35	620	440	0.54
"	28	15:41	770	160	0.16
"	29	12:42	1810	330	0.24
"	30	07:43	60	140	0.09
December	08*	21:10	520	250	0.41
"	12	23:26	11630	240	1.14

* Unlocated events.

Table 6 - Comparison between P-wave and total waveform for some parameters

Date 1989		Local Time	Seismic Energy (%)	PPA (%)	PPV (%)
October	21*	06:19	5	39	30
"	23*	01:23	49	100	100
"	25*	13:40	40	100	100
"	28*	01:02	51	100	100
"	28	07:58	9	72	32
"	30	15:53	6	100	26
"	30	15:57	23	85	55
"	30	15:59	14	50	56
"	30	17:05	8	57	43
"	30	21:18	11	70	52
"	31*	15:03	36	65	68
November	03*	18:07	13	61	44
"	05	05:24	59	100	100
"	19	05:54	10	88	66
"	19	05:54	14	100	100
"	19	05:59	27	100	93
"	25*	19:35	6	35	31
"	28	15:41	29	100	100
"	29	12:42	19	100	83
"	30	07:43	47	100	100
December	08*	21:10	2	12	7
"	12	23:26	12	100	50

* Unlocated events.

Table 7 - List of the seismic source parameters

Date 1989		Local Time	Corner Freq. (Hz)	Moment (GN-m)
October	21*	06:19	90	20
"	23*	01:23	90	15
"	25*	13:40	30	240
"	28*	01:02	80	25
"	28	07:58	75	785
"	30	15:53	15	34490
"	30	15:57	90	30
"	30	15:59	75	75
"	30	17:05	85	150
"	30	21:18	110	85
"	31*	15:03	85	10
November	03*	18:07	65	80
"	05	05:24	65	15
"	19	05:54	20	2400
"	19	05:54	10	6785
"	19	05:59	10	2215
"	25*	19:35	80	15
"	28	15:41	45	140
"	29	12:42	90	120
"	30	07:43	85	10
December	08*	21:10	45	50
"	12	23:26	20	4680

*Unlocated events.

Table 8 - List of stress drops, source radii, and slippages

Date 1989		Time	Stress Drop (kPa)	Source Radii (m)	Slippage (mm)
October	21*	06:19	2320	15	0.7
"	23*	01:23	1980	15	0.6
"	25*	13:40	970	50	0.9
"	28*	01:02	2035	15	0.7
"	28	07:58	59875	20	21.6
"	30	15:53	13120	105	27.7
"	30	15:57	3590	15	1.1
"	30	15:59	5265	20	2.0
"	30	17.05	16490	15	5.2
"	30	21:18	18685	15	4.7
"	31*	15:03	1170	15	0.4
November	03*	18:07	3380	20	1.5
"	05	05:24	590	20	0.3
"	19	05:54	2420	75	3.7
"	19	05:54	1280	130	3.4
"	19	05:59	615	115	1.4
"	25*	19:35	1180	15	0.4
"	28	15:41	2500	30	1.5
"	29	12:42	16160	15	4.8
"	30	07:43	830	15	0.3
December	08*	21:10	780	30	0.5
"	12	23:26	6480	70	8.9

*Unlocated events.

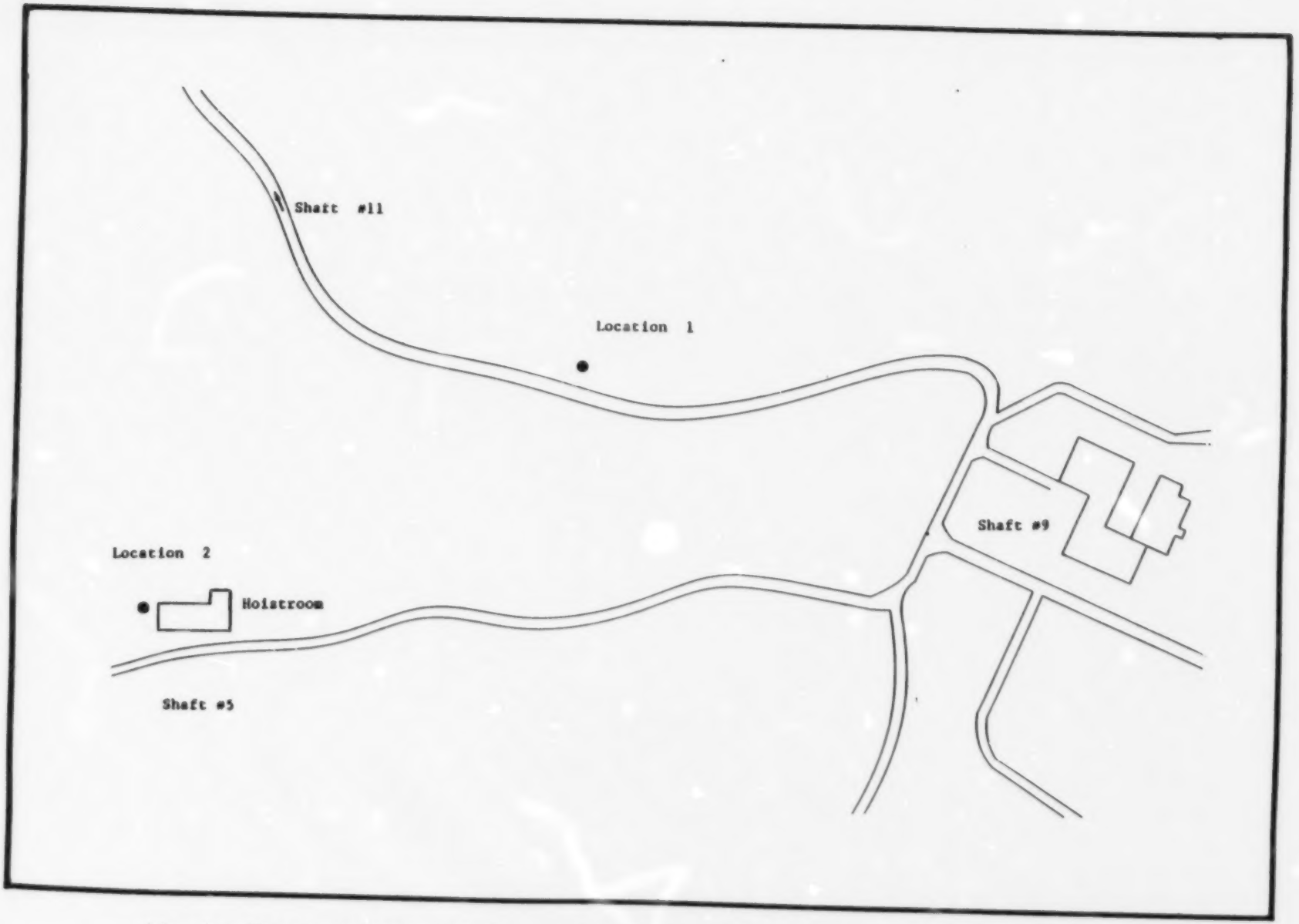

Fig. 1 - The two locations of the portable seismograph at Creighton Mine during the survey.

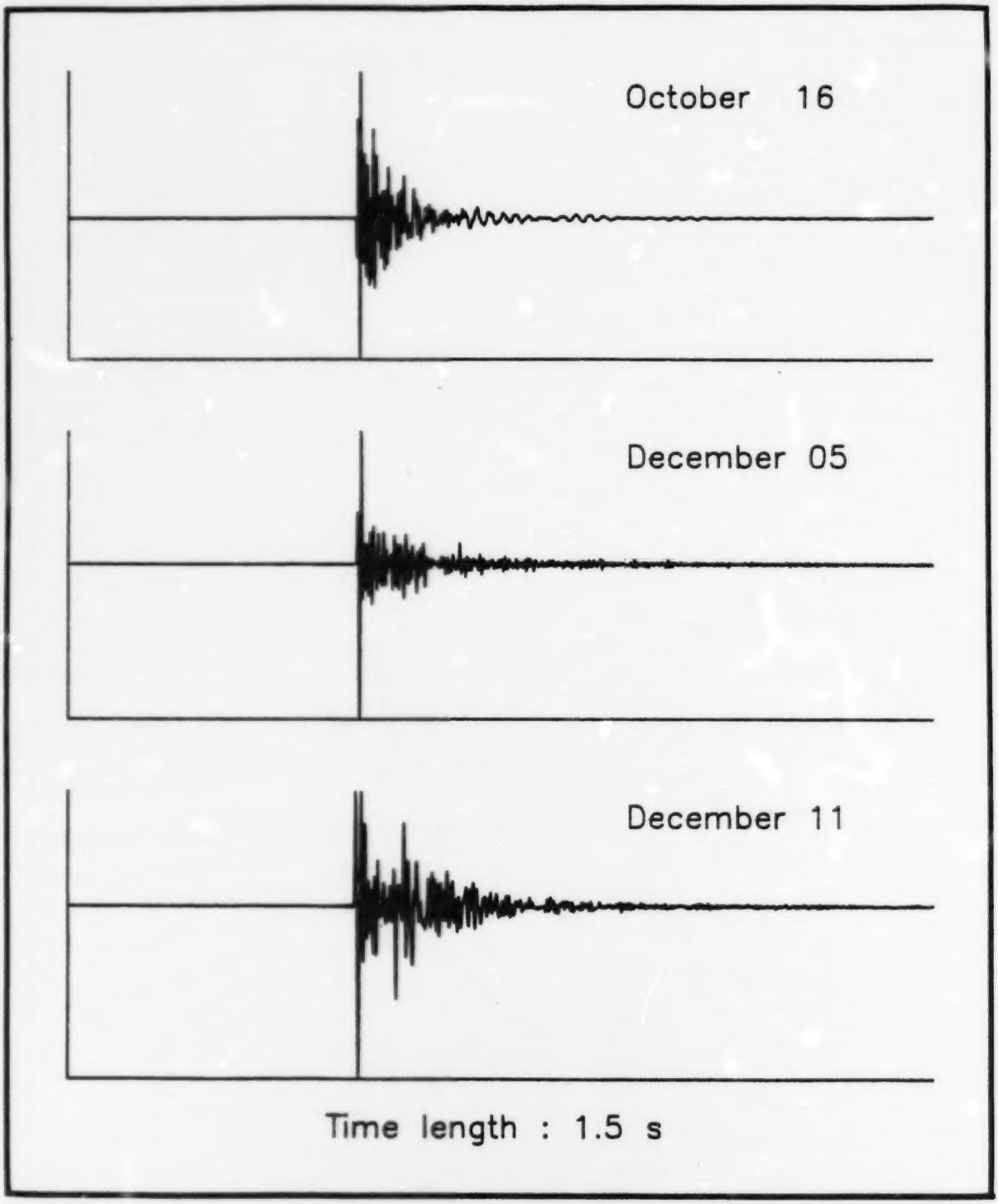

Fig. 2 - Signatures of the three unknown events as recorded on the z-axis of the sensor.

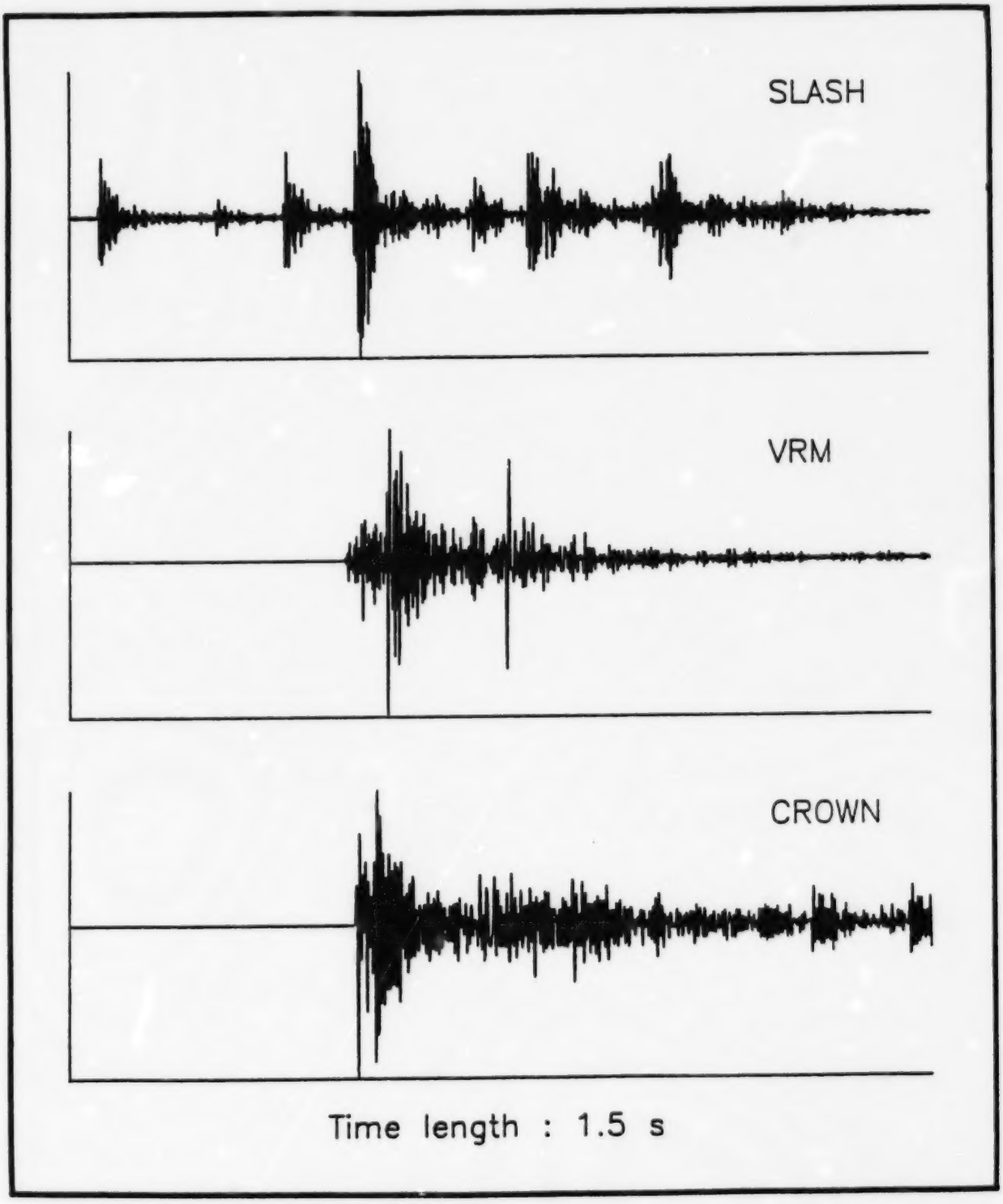

Fig. 3 - Distinctive signatures of three common types of blasts recorded during the survey.

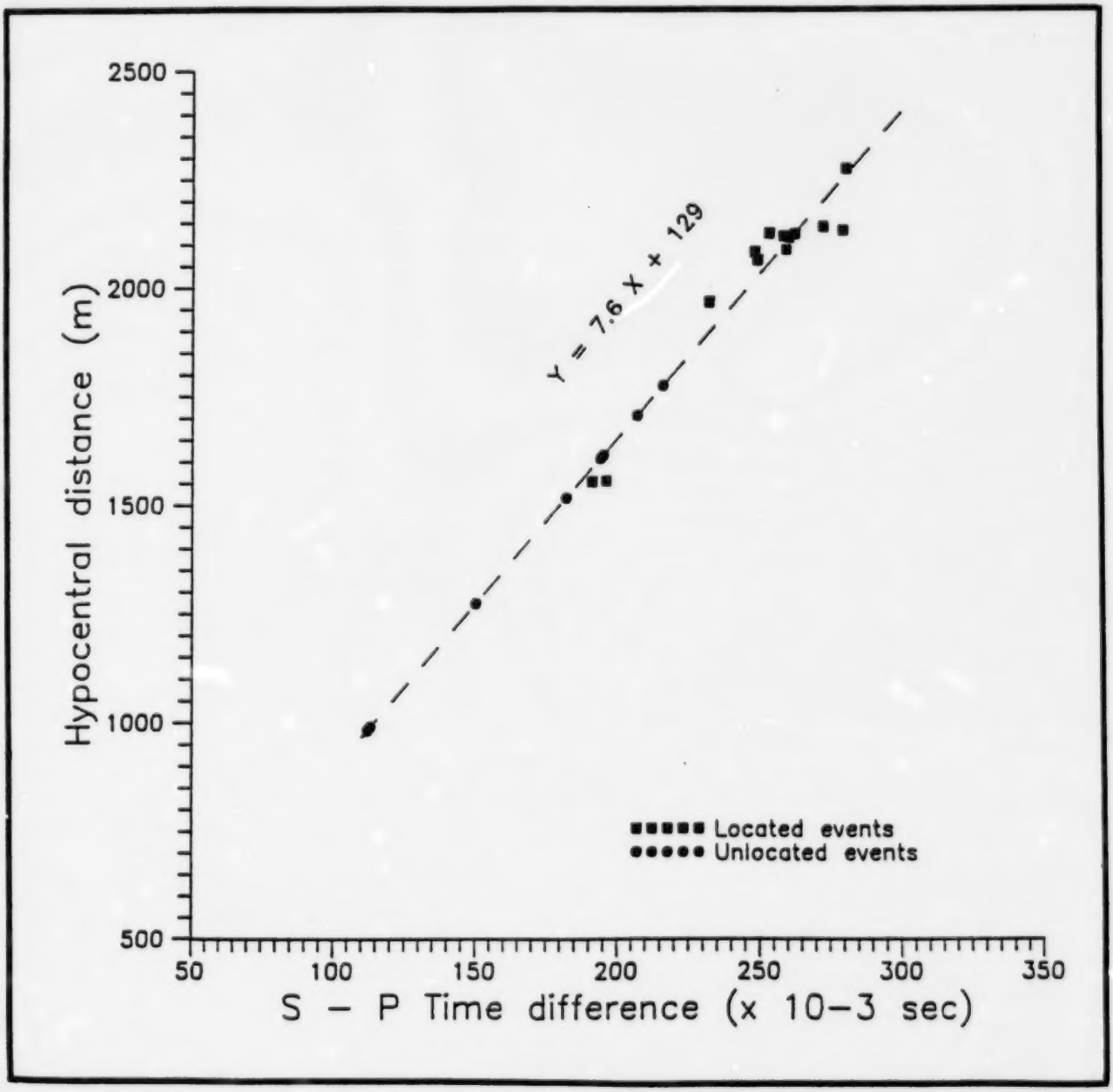

Fig. 4 - Relationship between S-P time difference and hypocentral distance.

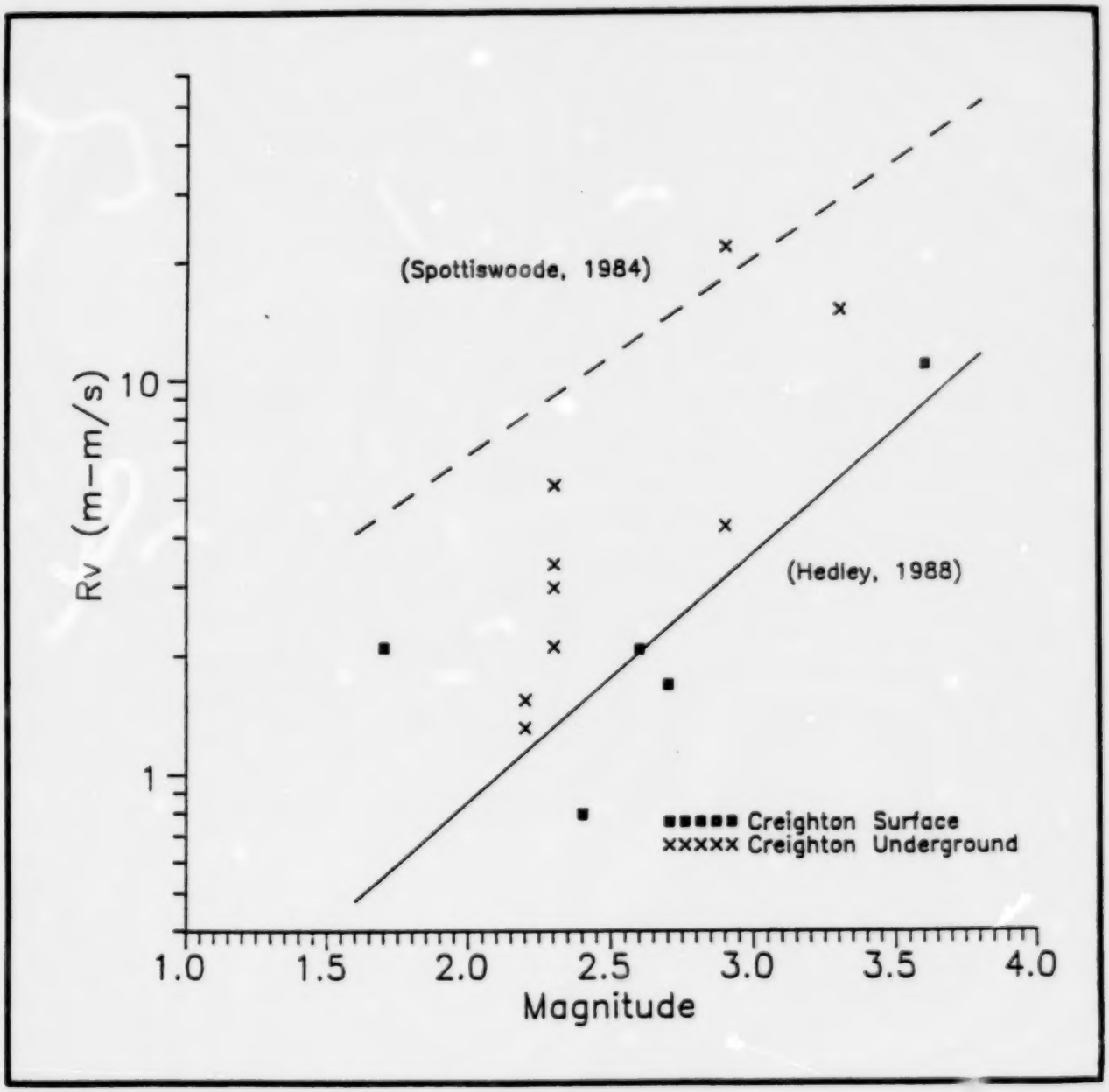

Fig. 5 - Peak particle velocity as a function of magnitude from Creighton Mine data compared to Spottiswoode and Hedley.

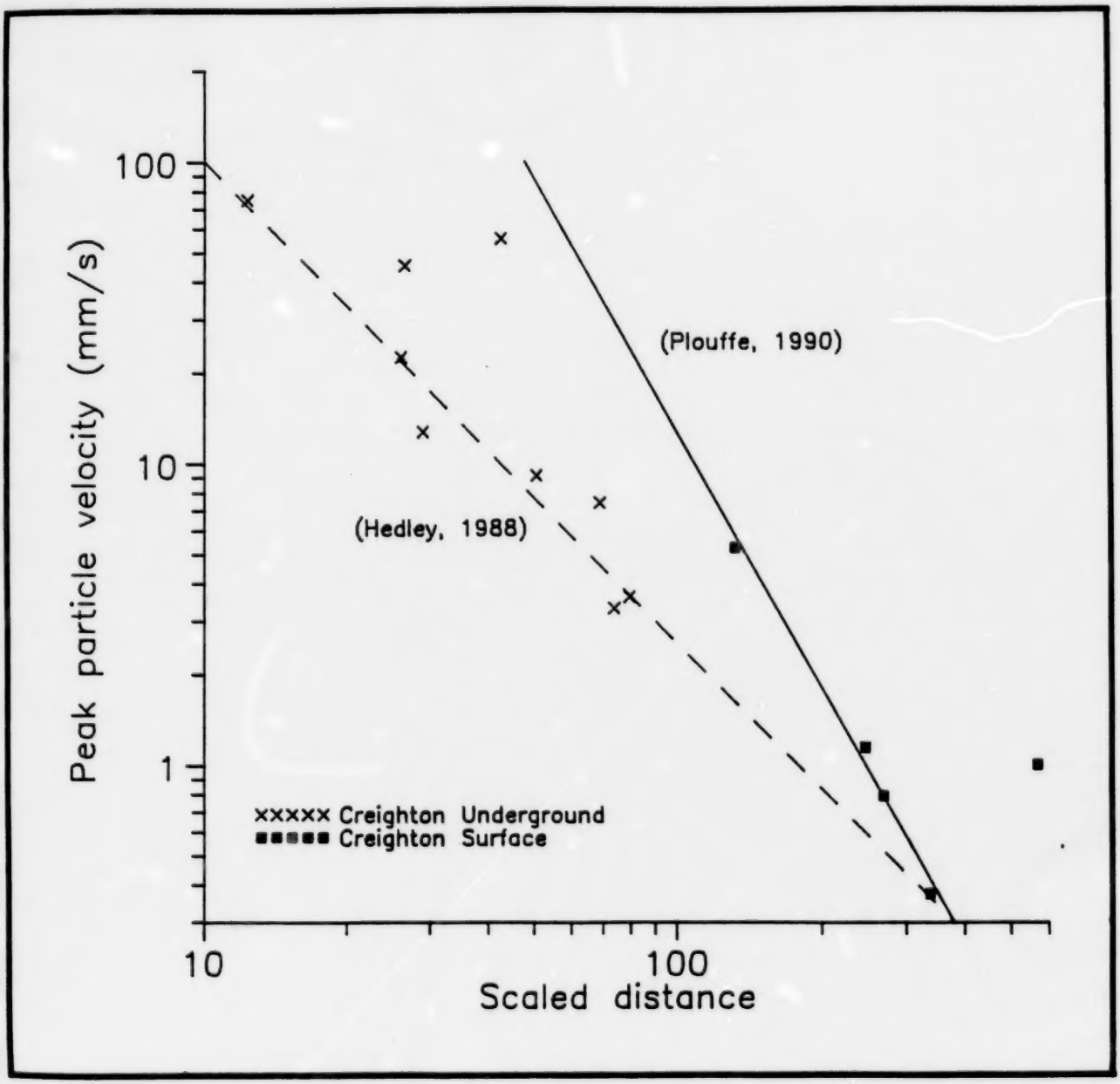

Fig. 6 - Peak particle velocity as a function of scaled distance ($R/M^{1/3}$) comparing underground and surface data from Creighton Mine.

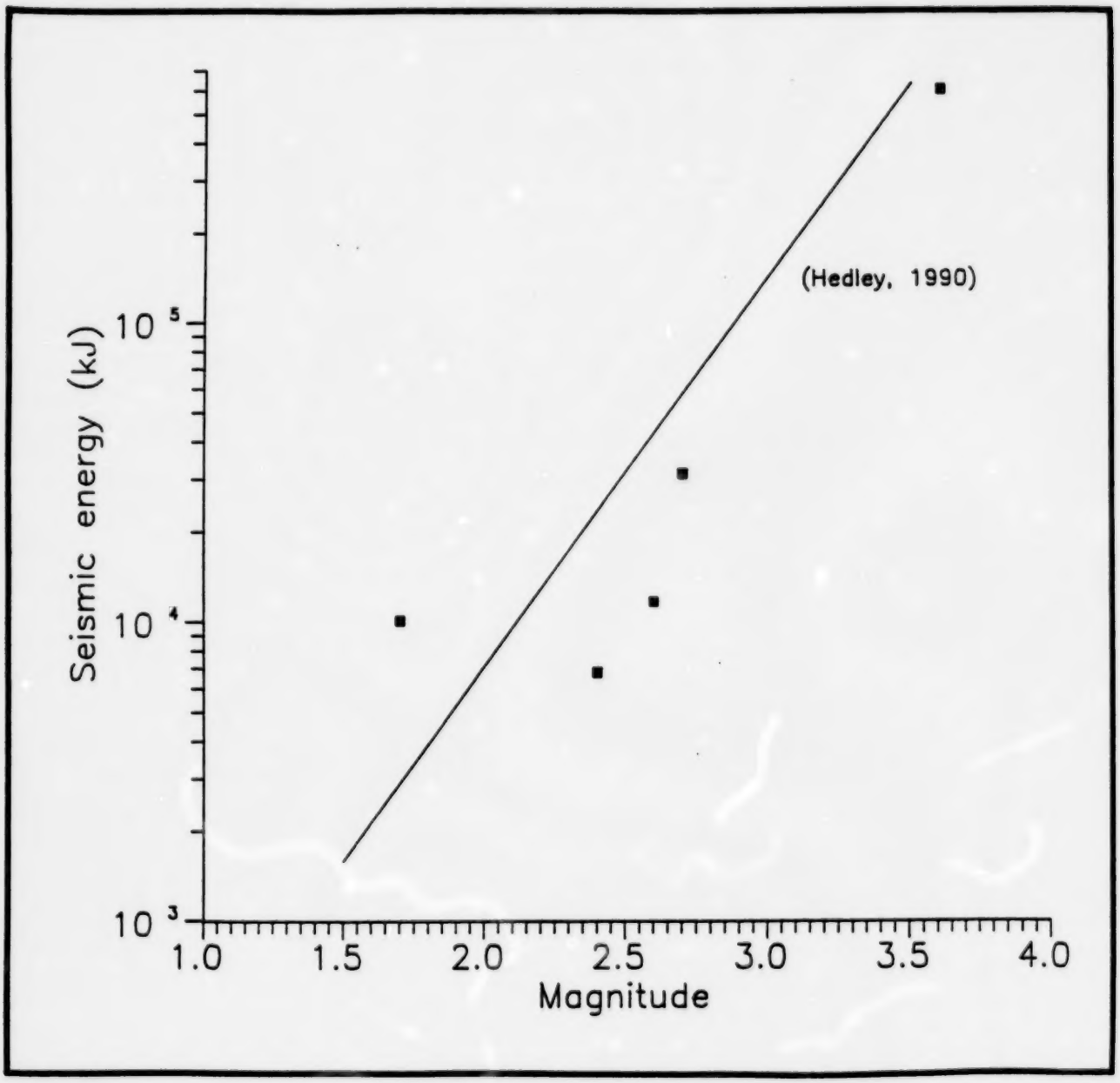

Fig. 7 - Relationship between seismic energy and magnitude.

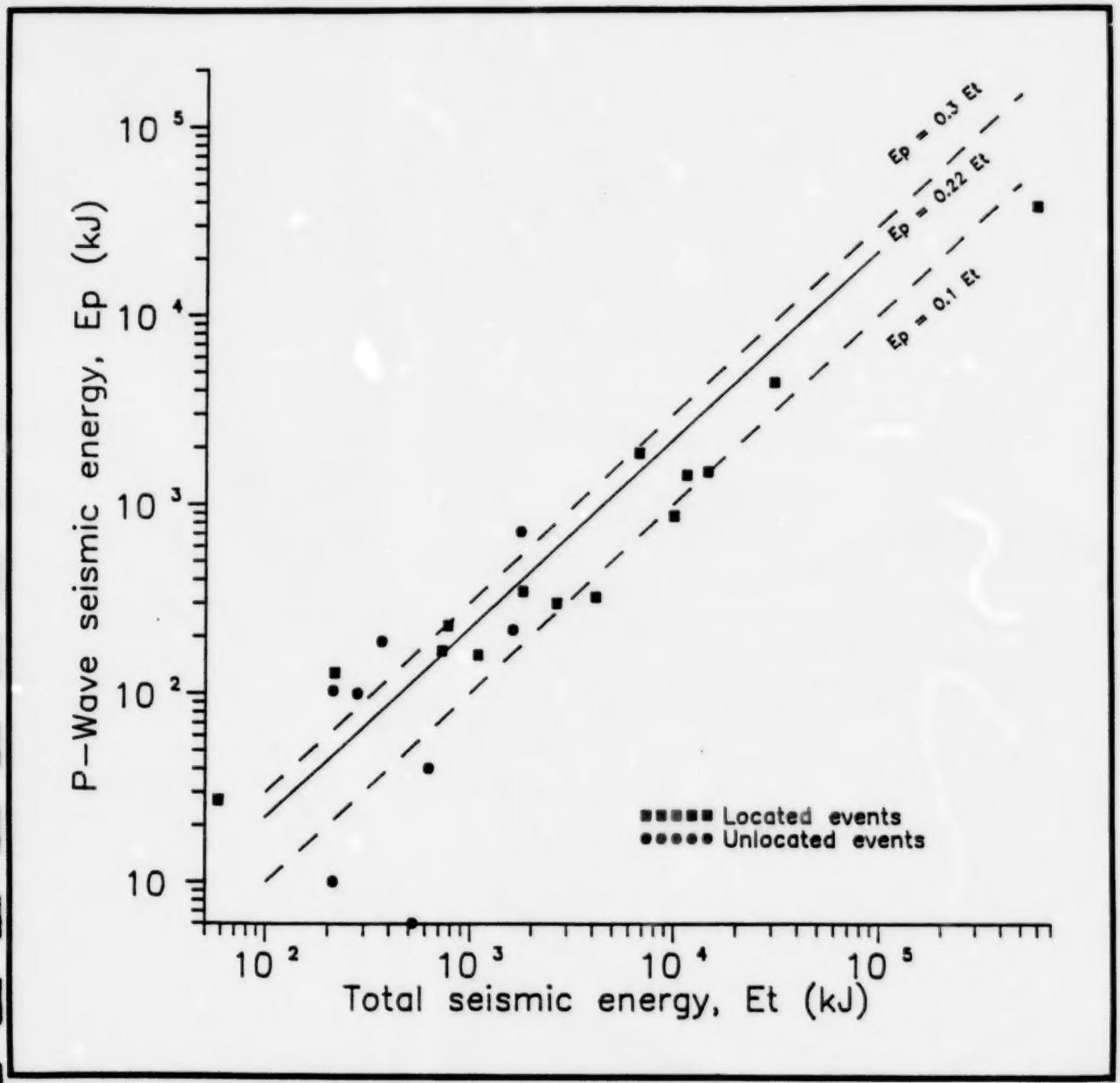

Fig. 8 - Relationship of the seismic energy contained in the P-wave compared to the total seismic energy.

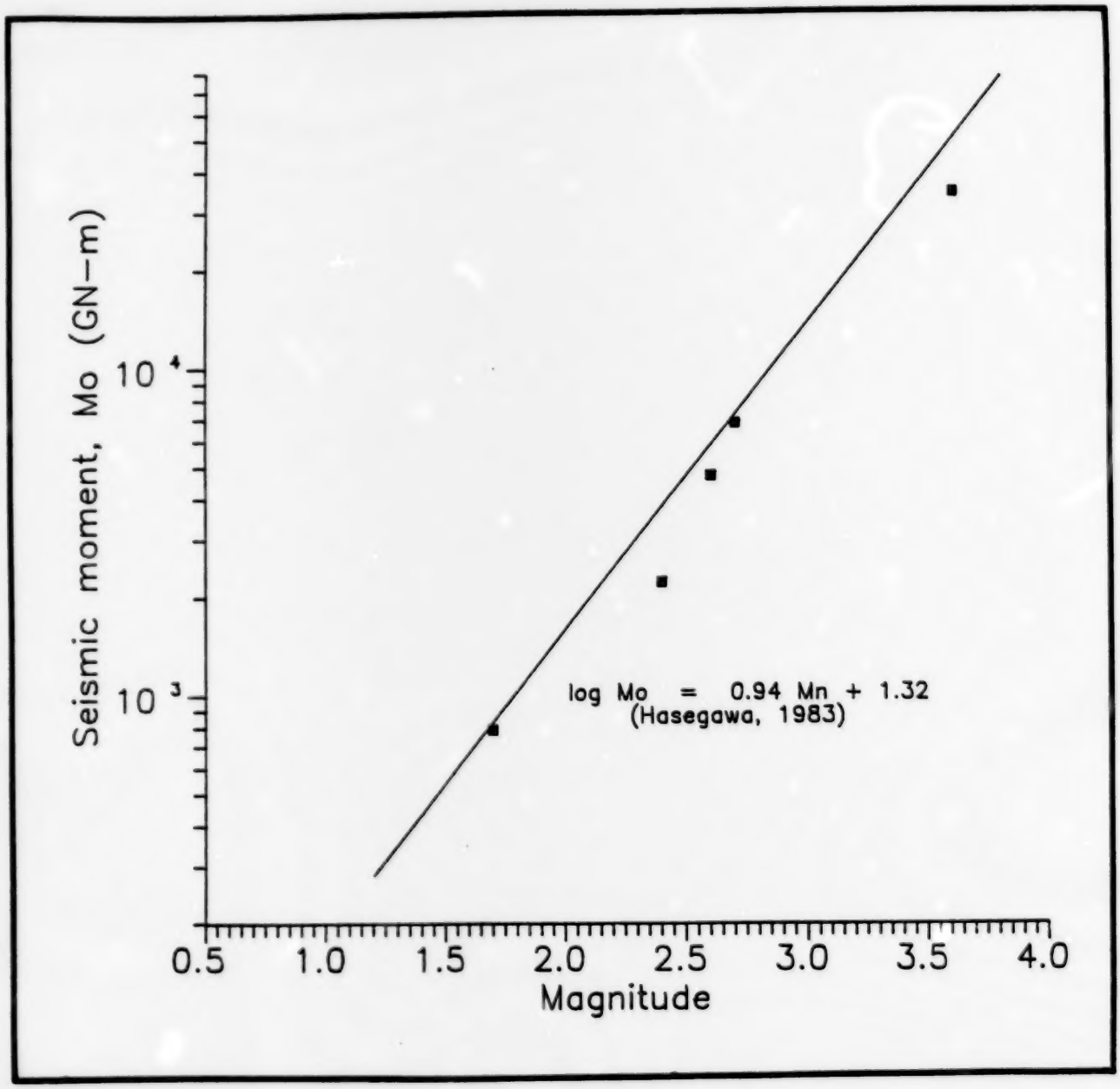

Fig. 9 - Relationship between seismic moment and magnitude.

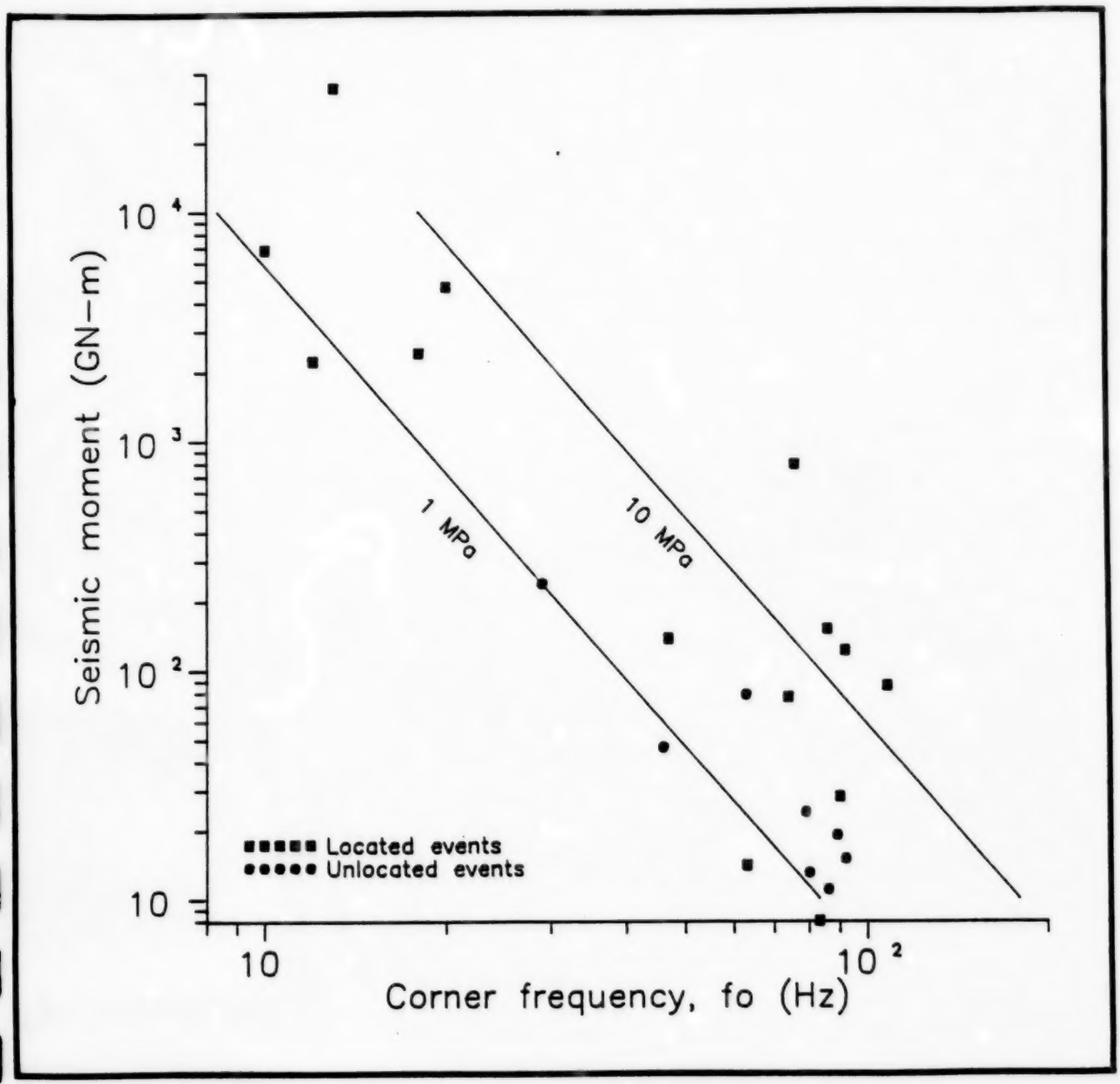

Fig. 10 - Relationship between seismic moment and corner frequency assuming a constant stress drop pattern between 1 and 10 MPa.

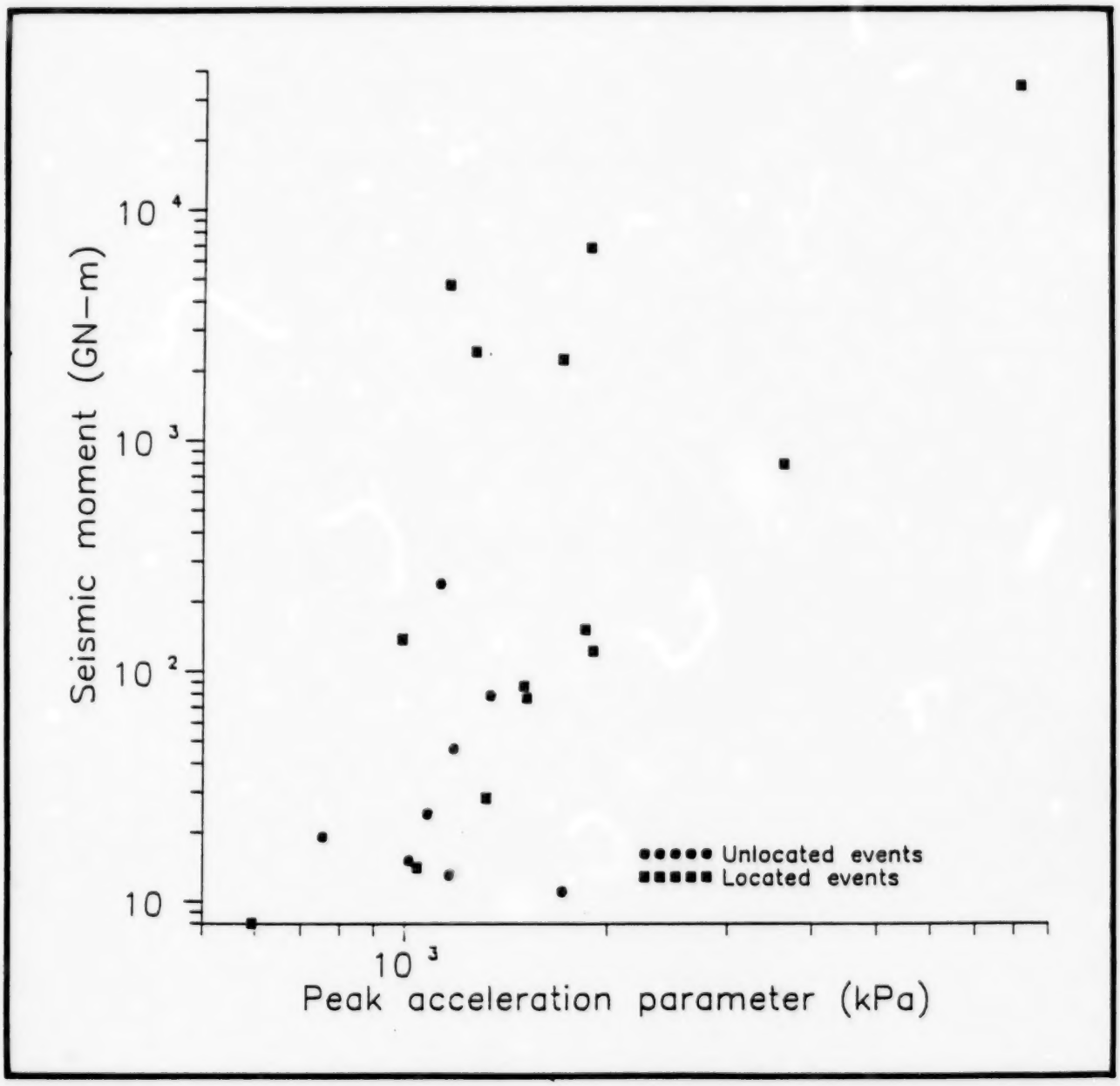

Fig. 11 - Seismic moment as a function of peak acceler..on parameter.

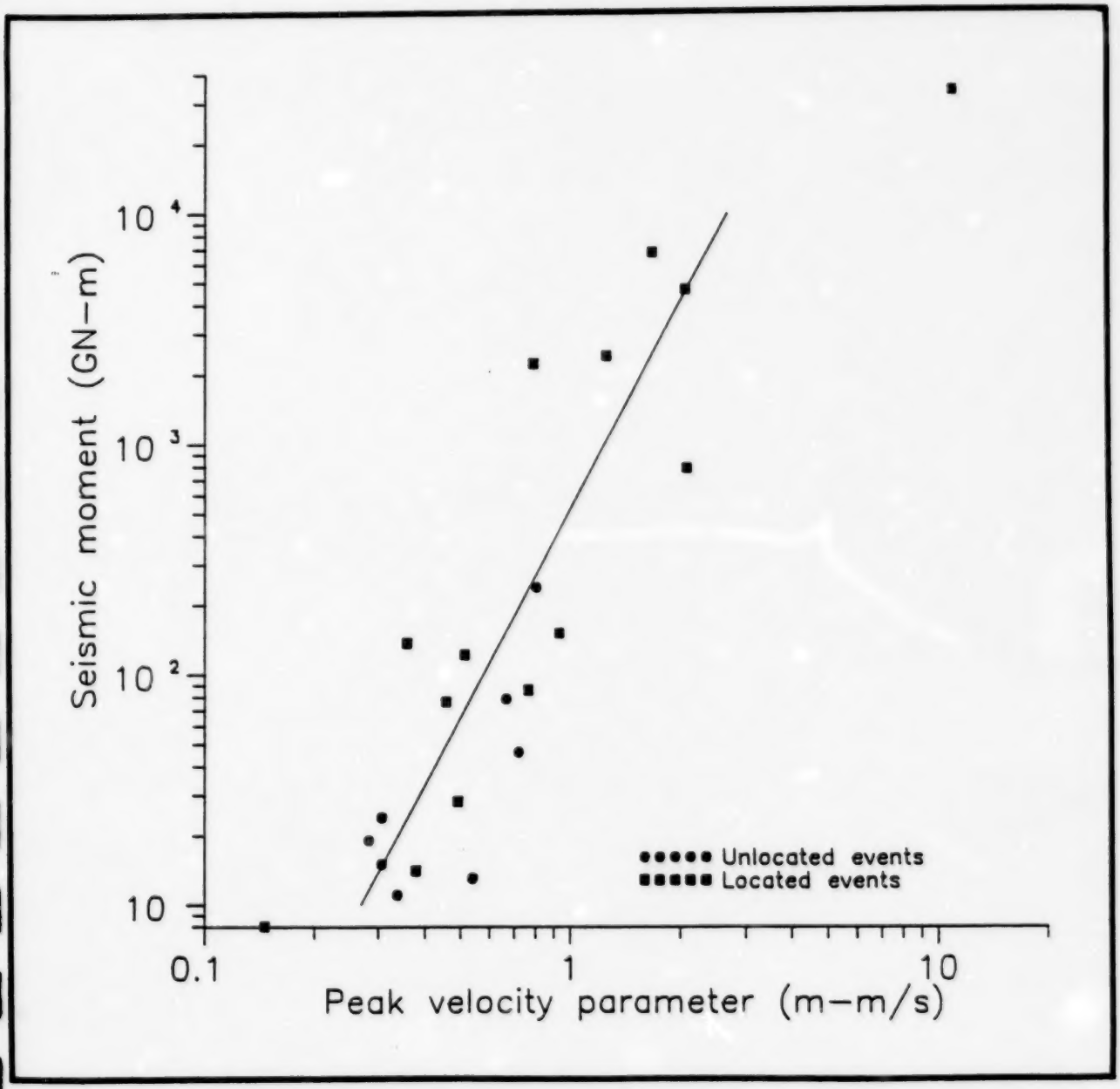

Fig. 12 - Seismic moment as a function of peak velocity parameter.

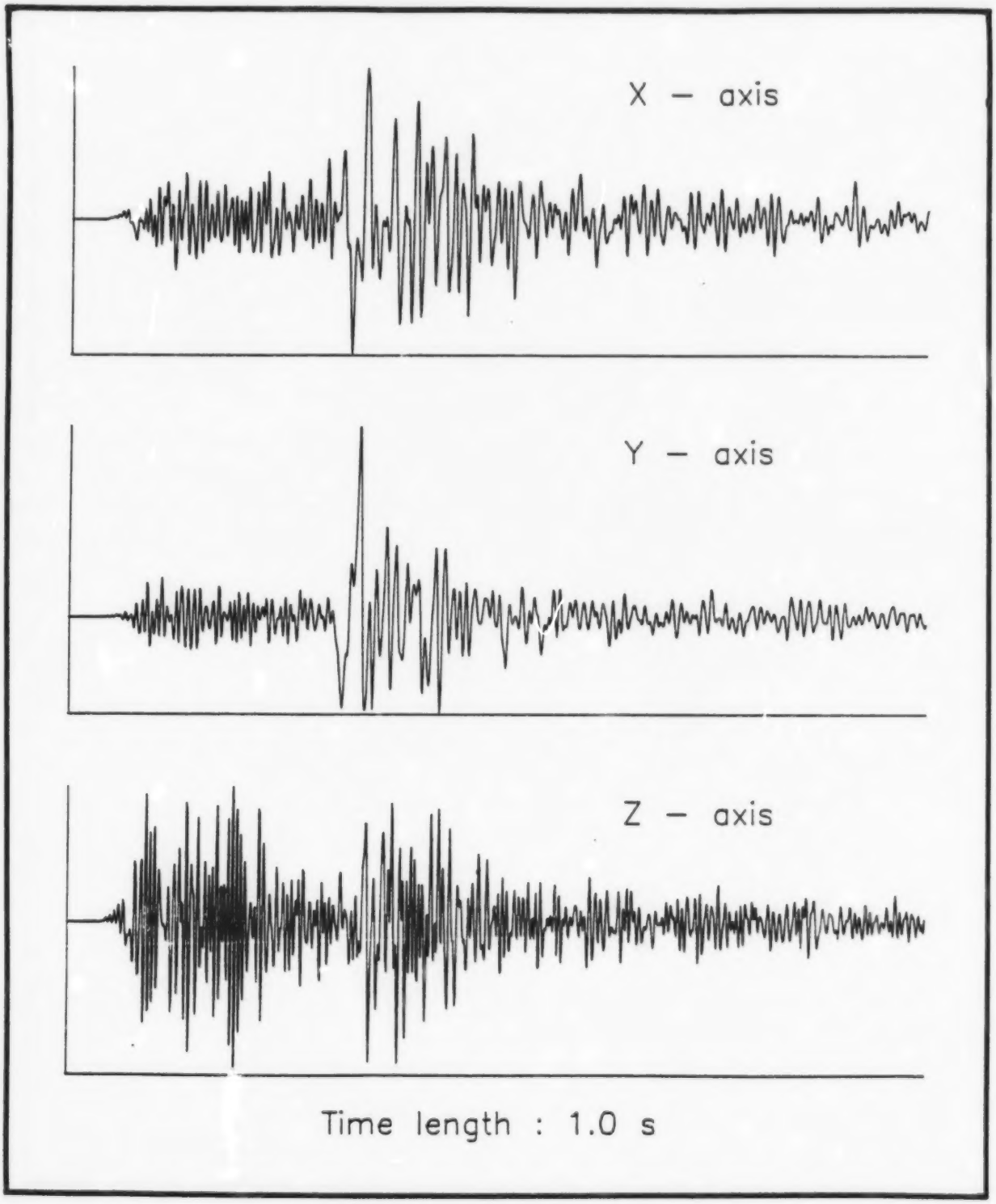

Fig. 13 - The October 30, 1989, event (magnitude 3.6 m_N) as originally recorded in acceleration mode.

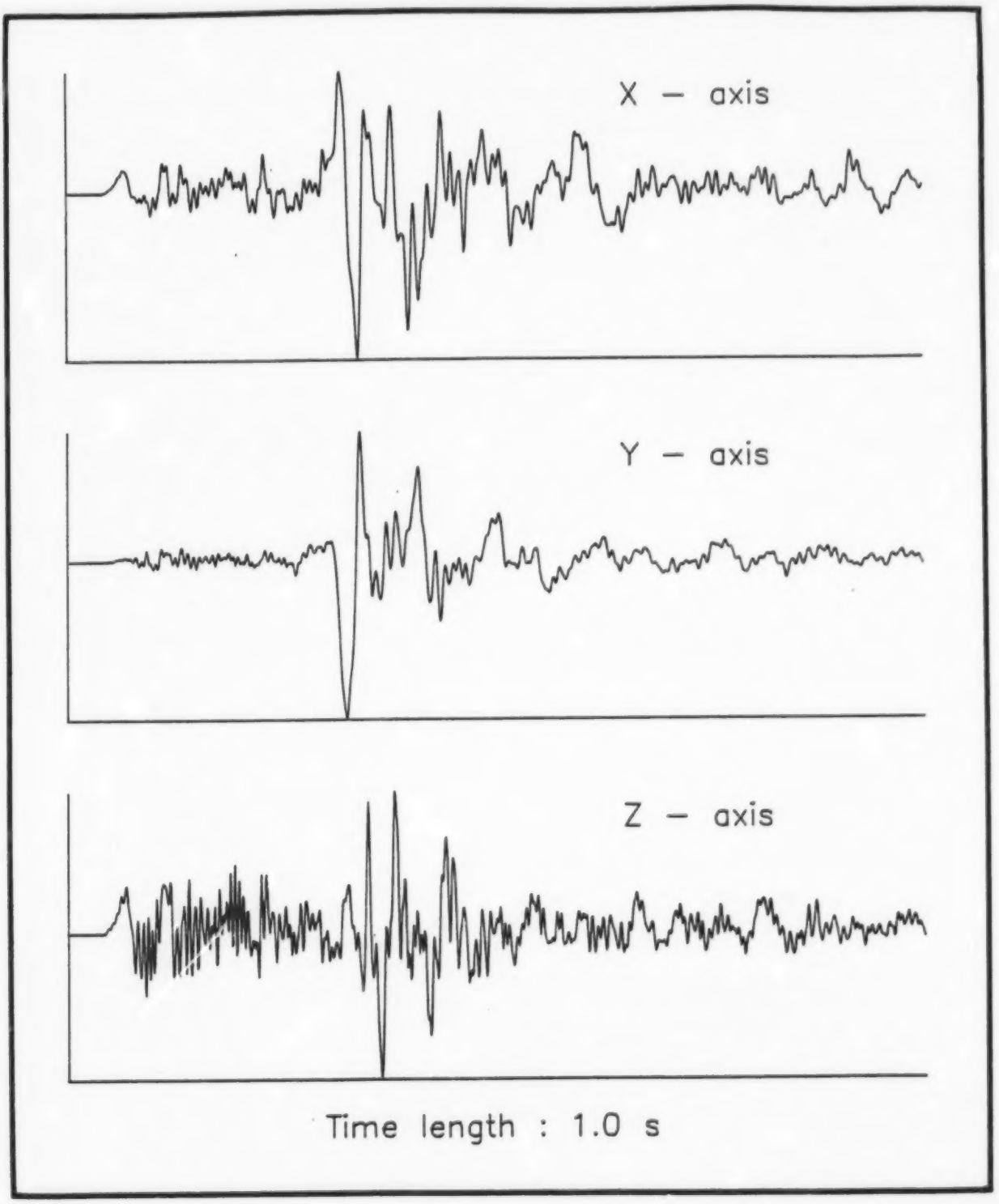

Fig. 14 - The October 30, 1989, event as integrated in velocity mode.

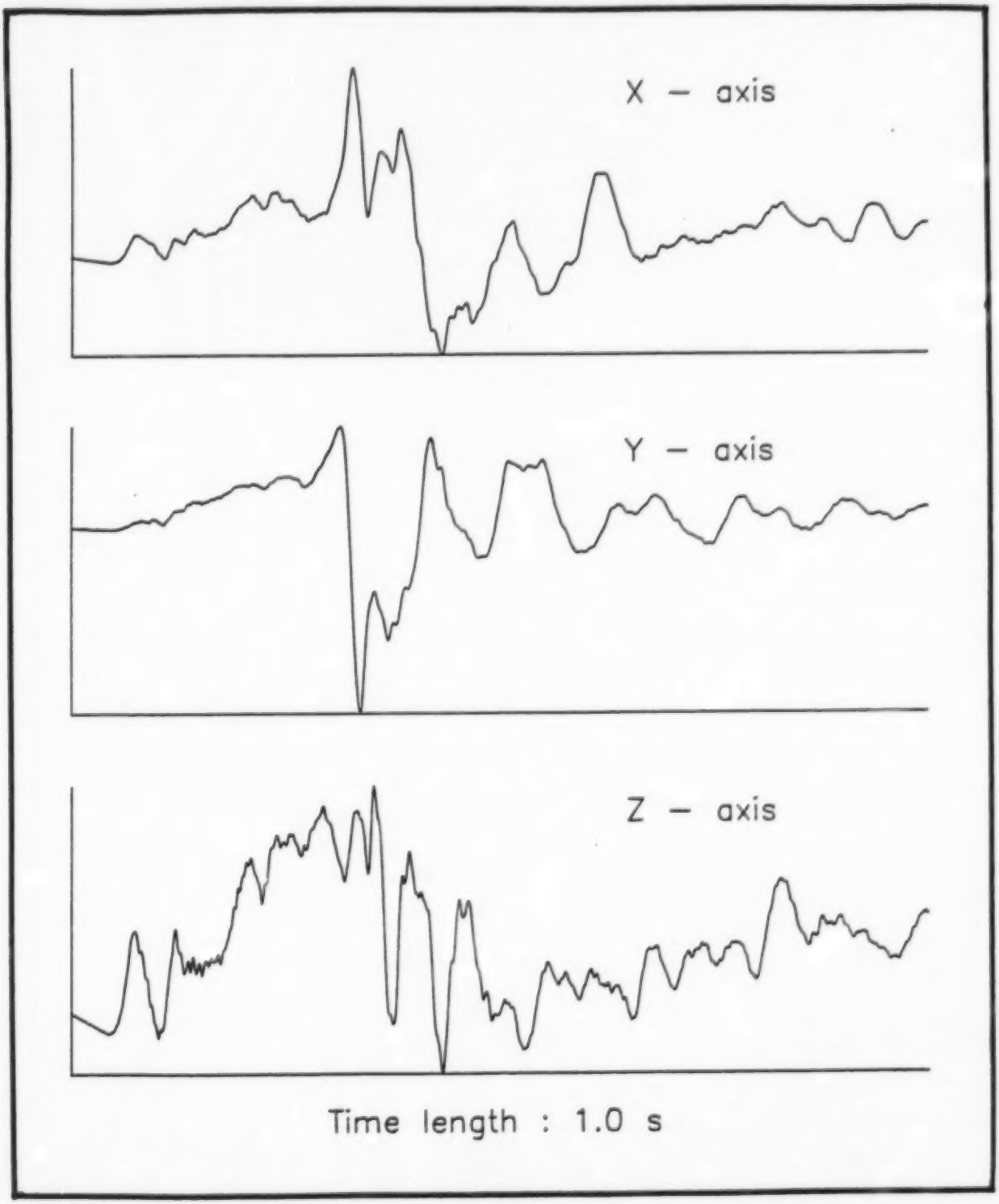

Fig. 15 - The October 30, 1989, event as integrated in displacement mode.

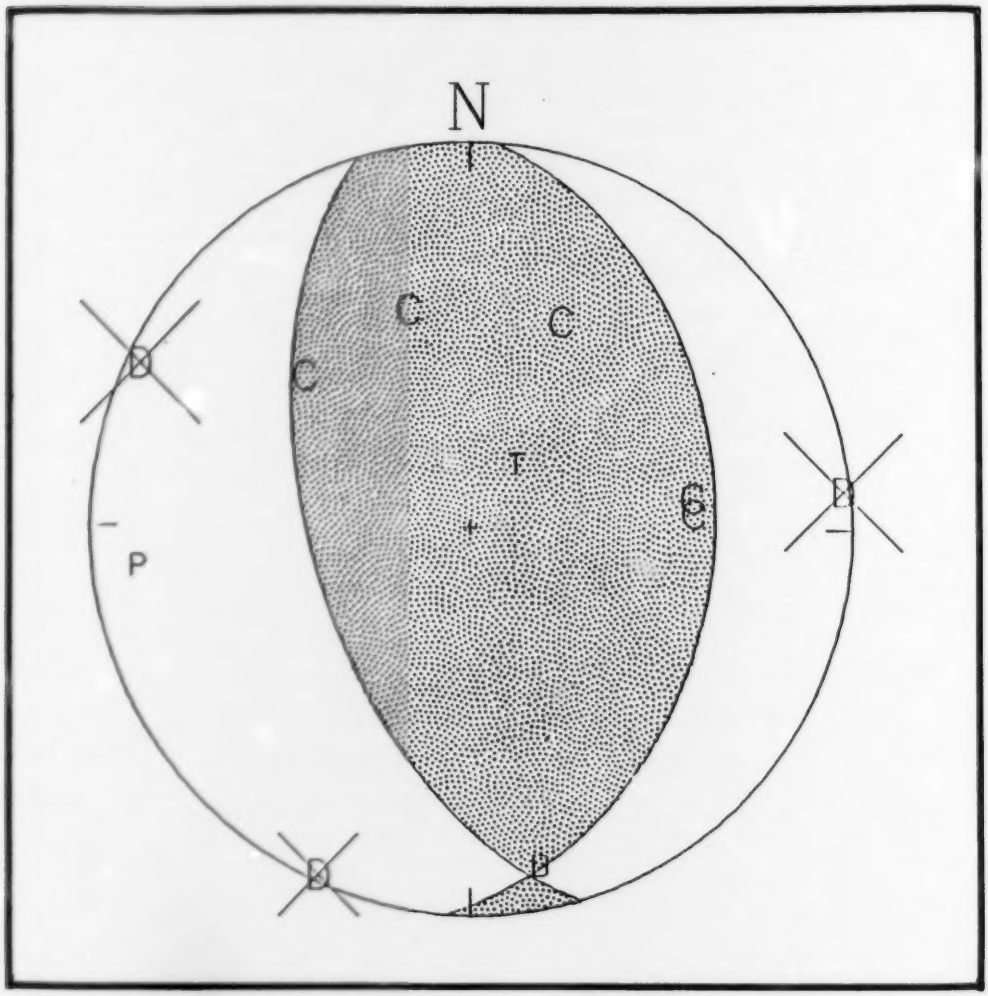

Fig. 16 - Preliminary focal mechanism for the October 30, 1989, event showing the first motions (C, D) and the amplitude ratios (X) as recorded by ECTN and SLTN.